The BAT-Probe
The Ultimate Tool to Measure Turbulence from any Kind of Aircraft (or Sailplane)*

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INTRODUCTION

Studying the atmosphere, in particular the atmospheric boundary layer, often requires measurements of turbulence and the vertical turbulent fluxes of water vapour, sensible heat, momentum and other quantities. Typical studies include the determination of evaporation and the sensible heat flux from the Earth's surface (soil, vegetation, ocean and other water bodies) for land use assessment or air-sea interaction processes, studies of the exchange of trace gases like CO_2 between vegetation and the atmosphere in the context of studies of Global Change, as well as studies investigating mixing processes in the upper troposphere or between the troposphere and the stratosphere. Another example are studies of the structure of thermals and the three-dimensional wind field around them.

Traditionally, a number of different instrumentation techniques were used for such measurements, amongst them the use of Inertial Navigation Systems (INS), smaller gyro systems, GPS attitude systems, differential pressure port systems at the nose section of research aircraft or moveable or rigid vanes mounted to nose booms. Most of these systems involved one or several very complex and expensive components and were usually only 'one-off' dedicated installations. None of these techniques could be used in small and inexpensive aircraft.

Viewgraphs:

- **NOAA P3 (5 pressure ports in the radome, boom**
- **CSIRO F27 (point out that the little box, the LTN51 INU, costs around $250,000)**
- **FIAMS aircraft (Cessna: 5 pressure ports in the radome and instruments for air temperature and humidity mounted on the conical section (clockwise: direct flow air temperature sensor, reverse flow air temperature sensor, reverse flow dew point mirror, Lymen-Alpha hygrometer); instrumentation pod under the wing of the Grob, with DLR five-hole probe and similar sensors mounted on or in the pod; Grob pod similar to pod developed by DLR for ASK-16s)**

The smallest platform capable of carrying instrumentation for such measurements were motorgliders, but the weight and power requirements of the instrumentation were stretching the aircraft's resources to the limit.

This paper introduces *the BAT-Probe* (it got its name from its shape - it looks like a baseball bat- but it also could mean "Best" Aircraft Turbulence Probe) as a means to overcome most of the above mentioned complexity of installation. It is an attempt to make the complex measurements basically independent of the platform by combining the latest sensor technology with powerful electronics and computing hard- and software into a small package. This package can be easily adapted to the widest range of platforms, ranging from Ultralight aircraft and UAVs (Unmanned Aerial Vehicles) to large transport category research aircraft or special purpose aerial platforms as, for instance, high altitude aircraft or even airships. It should also be possible to fly such a system on sailplanes.

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A prototype of the BAT-Probe is currently nearing completion under a collaborative project between NOAA's Atmospheric Turbulence and Diffusion Division (ATDD), The Flinders Institute for Atmospheric and Marine Sciences (FIAMS) and Airborne Research Australia (ARA).

Viewgraph:

- **The BAT-Probe (don't go into details at this stage, just mention that it is about 0.5m long, has a diameter of about 15cm at the front, carries most sensors around the hemispherical section and has its own built-in data system)**

MEASURING TURBULENCE

Measuring turbulence and turbulent fluxes from aircraft is a technologically demanding task. It involves, in general, the measurements of air temperature, humidity, pressures and the 3D-wind vector with high accuracy and at sampling rates of tens of Hertz. Fast sensors for air temperature are available, are light-weight and do not require much space and electrical power. Fast sensors for humidity are more difficult to design, but there are systems available which can be mounted on small aircraft. Until recently, the main problem was to measure the 3D-wind vector accurately.

Wind measurements from an aircraft require observation of the wind velocity relative to the sensors and the velocity of the sensors relative to the Earth. The 3D-wind vector is then found as the small resultant vector sum of these two large vector velocities.

None of the two large vector velocities can be measured directly, but require the measurement of a number of other parameters, amongst them, the angles of attack and sideslip of the aircraft, the aircraft's heading and its pitch and roll angles, 3D-accelerations of the aircraft, its angular rates and more. All measurements have to be combined in a very careful manner, without phase shifts or other inconsistencies between them, to derive the two large vector quantities. For most applications, it is also essential to know the position of the aircraft accurately at all times.

Viewgraph:

- **Schematic for wind and turbulence calculation (it should not be necessary to go into much detail with this diagram; only point out the main principles: attitude measurements required for both, 3-D ground speed and 3-D air speed vectors; requirement to measure angles of attack and sideslip, accelerations)**

All of these measurements obviously also need to be logged on a computer for processing.

THE BAT-PROBE

Viewgraph *(same as shown above)*:

- **The BAT-Probe (identify items shown as they appear in the text, also keep the viewgraph for later reference)**

The BAT-Probe combines (low-cost) sensors for pressure, air speed, angles of attack and sideslip, 3D-acceleration and air temperature with differential GPS systems for high precision position, ground speed and attitude (aircraft pitch and roll angles and heading) measurements packaged together in a small stand-alone package. The probe contains its own 16-bit A/D-unit which converts the measurements to digital values directly at the sensor location and transmits the data in a serial data stream to a PC-based real-time processing computer. As the probe is small and relatively low cost, it becomes possible to mount it to just about any aircraft platform without the necessity of substantial airframe modifications.

Combining the sensors at one location in close proximity of the A/D-unit minimises possible attenuation of the small signal voltages. The small size of the probe with its very short pressure lines between the pressure ports and the pressure transducers also virtually eliminates problems with time lags or resonance effects in pressure lines.

The sensor package itself was mainly developed under NOAA/ATDD responsibility, while FIAMS developed the A/D-unit and associated digital electronics. Both organisations have joint responsibility for the low- and high-level software development.

Although, as said before, the BAT probe got its name because it looks like a baseball bat, the following viewgraphs will explain why it really is the "Best" Aircraft Turbulence probe.

PROBE CHARACTERISTICS

The probe weighs about 4kg and requires about 50 W of 10 to 30 VDC power. Like a sonic anemometer, data is received serially at 50 Hz.

The housing consists of a 15-cm diameter hemisphere supported by a truncated circular cone. Its carbon-fibre construction is light but very strong. Further, carbon-fibres attenuate any potential electromagnetic interference.

Mechanical and electrical installation on any aircraft is simplified by placing electronics and sensors within the housing. Relative winds are computed from the pressure distribution observed at nine pressure taps on the sphere. Two unique features of the BAT probe are the method of measuring static pressure and atmospheric temperature.

MEASURING PRESSURES

Viewgraph:

- **Nine Hole Pressure Sphere (also show on BAT-Probe viewgraph); on the hemisphere, there are nine holes, a large centre hole, and two sets of holes arond the centre hole, open circles are large holes, crosses are small holes; the equations shown are those for V_a (3-D air speed); T_s (static air temperature); α (angle of attack); β (angle of sideslip); q (pitot pressure); P_s (static pressure).**

Static pressure is difficult to measure on an aircraft because the sensed pressure is easily contaminated by flow distortion about the static ports and airframe. The BAT probe mitigates static error by its unique 9-hole design. With the BAT probe, static pressure is obtained from a pneumatic average of the four pressure taps placed 41.8° aft of the Design Stagnation Point (DSP) and 45° off vertical. At zero angle of attack (when the instantaneous stagnation point is coincident with the DSP), the BAT probe correctly senses static pressure. However, like a conventional Pitot probe, static pressure is increasingly underestimated with increasing angles of attack. With this approach, the static error is less with the BAT design and an analytical model exists to remove the error.

Solid state precision compensated, low pressure sensors form SenSym (for example model SCXL004) or Data Instruments (Model series XCX) are used. Such pressure sensors have a frequency response approaching 1kHz with an accuracy of around 0.2% of their full scale reading. Furthermore, the sensors are heated to reduce temperature related drift.

The actual sensor choice is optimized for the design flight speed. As a result, sensors with unnecessarily large ranges are not used and accuracy within the desired sensing range is high. For example, a ±12hPa sensor is usually used on angle of attack and sideslip pressure ports. This yields an accuracy of ±0.05hPa. Such accuracy is not possible with more conventional aircraft sensors. An added advantage is the cost of our sensors -around US$50.

AIR TEMPERATURE

At aircraft flight speeds, the observed temperature is contaminated by compressibility effects. Correction of the sensed temperature is functionally dependent on dynamic and static pressure. The BAT probe places a micro-bead sensing element within the DSP where both dynamic and static pressure are known accurately and at high frequency. The DSP port is designed to ventilate the micro bead at 10m/s with small thermal housing influence. The resulting housing sensor combination has a 0.07s time response that is much faster than more conventional housings/sensor combinations.

Viewgraph (*same as above*):

- **The BAT-Probe (show where temperature sensors are mounted)**

For fast temperature measurement, a Victory Engineering Corp's 0.005" micro-bead thermistor is used. Within the BAT housing, they have a time response of 0.07s that is ten times faster than a fast Rosemount sensor housing combination. On the other hand, the BAT probe temperature sensor is more fragile. Although the housing design is great for fast response and observing the micro-beads pressure environment for use in temperature recovery computations, it offers the micro-bead little protection from foreign object damage (bugs, rain drops etc.). Regardless, this has not been a serious problem as micro-beads are infrequently damaged. To further mitigate this concern, the BAT probe electronics allow installation of twin micro-beads.

POSITION, VELOCITY AND ATTITUDE

The BAT probe relies strongly on DGPS technology and does not require any gyro-based systems. In the past five years, Differential GPS (DGPS) techniques have developed into a powerful measurement utility. Currently DGPS measurement techniques allow dynamic observation of position, velocity and attitude at 10Hz and with accuracy of ±0.5m, ±2cm/s and ±0.05° respectively. If necessary, accelerometers can be used to extend these observations to higher frequencies.

Modern GPS technology overcomes a wide range of problems of earlier techniques Amongst them are:

Viewgraph:

GPS and the BAT-Probe

- Digital precision with no calibration
- Low power requirements
- Simple mechanical and electrical installation
- Small size and low weight
- No moving parts
- Output in earth coordinates
- World-wide operation
- Highly accurate time base

Position is required to document aircraft location and is not needed for wind computation. Regardless, simple DGPS allows documentation of position to ±3m. Where necessary, extension to high accuracy sub-meter techniques is not difficult.

Using Doppler DGPS techniques, observation of probe velocity to 20Hz and at an accuracy of ±2cm/s is simple. A main advantage of DGPS approaches is that one obtains the velocity of the probe (the antenna is in the probe) in Earth coordinates. Again, accelerometers within the BAT probe can be used to extend velocity frequency response to 50Hz.

Viewgraphs:

- **Velocity of Sensors V_s (V_s is computed as a mix of GPS measurements and integrated accelerometer measurements; will only show example of spectra)**
- **Spectra: W_s (note the high frequency tail as determined from accelerometers; GPS measurements level off at about 1Hz)**

Attitude is important since winds relative to the BAT probe must be rotated to Earth coordinates. Attitude, at 10Hz and with an accuracy of ±0.05°, is obtained from a Trimble TANS VECTOR GPS attitude receiver. Although 10Hz may be fast enough for large aircraft, it is not for smaller aircraft with less inertia. For smaller craft, GPS attitude output is low-passed then mixed with high-passed twice integrated differential acceleration observations. The result is attitude, at 50Hz and with an accuracy of ±0.05°. Four small GPS patch antennas must be installed for use of a TANS VECTOR system. The BAT-Probe housing can be used to house one antenna.

Viewgraphs:

- **Vector Attitude (θ is pitch angle; will only show example of spectra)**
- **Spectra: Platform's Pitch Angle (note again high frequency tail from accelerometer measurements)**

The quality of the wind and turbulence measurements can be assessed by flying a phugoid motion pattern with large, pilot-induced vertical motions. If this manoeuvre is flow in a smooth air mass where no vertical winds are expected, the instrumentation should be able to measure a near-zero vertical wind component. As both, the vertical motion of the aircraft and the "vertical true air speed", are large vectors for the given case, even small errors in their computation would lead to substantial errors in the measured vertical wind speed.

The following viewgraph shows time traces from such a test. As can be seen, the resulting vertical wind is less than about 10cm/s during manoeuvres with vertical aircraft speeds of nearly 5m/s.

Viewgraph:

- **Vertical Component of wind during phugoid motion (W_s is vertical speed of aircraft; W is vertical wind speed; W_a is "vertical true air speed")**

DATA SYSTEM

Viewgraph:

- **BAT-Probe data system**

The A/D system was developed by FIAMS to provide high speed, high resolution, multi-channel data logging. The system consists of two boards with an 8 pole low pass (anti-aliasing) filter for each of eight channels combined with an 8 channel multiplexer and an intelligent 16 bit A/D board. The three boards together comprise a signal conditioned, 16 channel, 16 bit A/D system with serial output. A custom ISA serial board provides an intelligent interface to a PC.

The system is unique in its combination of high speed, high resolution, high channel count, and on board intelligence. Software filters and other operations may be implemented on the A/D board, relieving the PC processor from such simple, but time consuming tasks. Additionally, multiple systems may reside on one PC, allowing for very high channel count systems.

The hardware and firmware are configured to provide 50Hz data output from the 16 channels. Each of the 16 channel is first conditioned by the 8 pole 30Hz low pass (anti-aliasing) filter. Then it is interrogated or over sampled 32 times by the 16 bit A/D. The resulting data is averaged and then serially transmitted and timed tagged to ±1ms based on the 1sec pulse available from the GPS receiver.

INSTALLATIONS

The first prototype BAT probe, combining NOAA and FIAMS technology was completed February '97. However, the housing with sensors has been flying on the NOAA *Long-EZ* for the last five years. Similarly, the A/D system has been used by Flinders for the last three years. Probe installation is planned or under way on the following aircraft.

Viewgraph:

- **LongEZ, Ultralight (note also the IRGA (Infra-red gas analyser) for fast water vapour and CO_2 measurements mounted just behind the BAT-Probe)**

The NOAA Long-EZ Aircraft (N3R)

The BAT housing and sensors were first installed on the *Long-EZ* in 1989. During 1991, differential GPS technology was added. Many improvements have been incorporated each year. Currently, the *Long-EZ* installation is used in three to five studies every year.

The Quicksilver GT 500 Ultra-light Aircraft (NOAA 1)

NOAA's Atmospheric Turbulence and Diffusion Division is instrumenting two Quicksilver GT500 Ultralight aircraft with a BAT probe to support the NSF SHEBA project in the Arctic.

Viewgraph:

- **Grob G109B (BAT-Probe not shown; it will be mounted under the r/h-wing together with an IRGA)**

The FIAMS/ARA Grob G109B Aircraft (VH-HNK)

The prototype BAT probe is currently being installed and tested on the Grob G109B aircraft.

Viewgraph:

- **Grob G520T Egrett**

The ARA Grob G520T Egrett Aircraft (D-FARA, VH-ARA)

In a collaborative project with DLR, three BAT probes will be installed on the Grob G520T *Egrett* high altitude research aircraft this summer. One probe will be installed high on the tail with an additional probe placed six meters outboard on each wing. This gives a symmetrical installation with high redundancy and greater turbulent resolution. The first field use will be in a project to measure turbulence near the jetstream over the Mediterranean Sea.